SUMMARY OF PRECISION ACTUATORS FOR SPACE APPLICATION

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INTRODUCTION

The objective of this paper is to present the state-of-the-art of precision actuators for space application in the United States. This report is based upon information available to the author and not on a comprehensive search of all the developments in the US. Precision actuators are those with submicron resolution and often limited to less than about .2% strain of the actuator material. Most of the actuators are those associate with Adaptive Structures. One definition of Adaptive Structures are systems whose geometric and physical structural characteristics can be beneficially modified to meet mission requirements either through remote commands or automatically in response to internal or external stimulations. Actuators, sensors and control systems are directly integrated into the structure.

One diagram showing the interactions proposed by Wada et al. (1990) is shown as Figure 1. Wada and Garba (1992) presents the need for Adaptive Structures and precision actuators for space structures. Additional information on Adaptive Structures and the various actuators are available in the proceedings of conferences on Adaptive Structures edited by Wada, Matsuzaki and others (1991., 1992 and 1993).

Actuators are essential and often limit the ability to implement many concepts and the performance of Adaptive Structures. Since the actuator strain must be transmitted into the structure, actuator is required to have a modulus of elasticity comparable to structural materials. The actuators in this report are those currently available for application such as piezoelectric (PZT), electrostrictive (PMN) and magnetostrictive materials.

The paper briefly describes the actuator, its integration with the structure and the role of the actuator in meeting the structural performance requirements. Where applicable, the report includes the performance and environmental requirements on the actuator and the desirable characteristics as information for actuator/material researchers. Information on commercial actuators is not presented.

ACTUATORS

In-Line Actuators, Small Stroke

As discussed by Wada (1992), many of the large or deployable space structures are truss type structures because they are more efficient and more readily deployed or constructed in space. Future space programs will require large precision space structures, an example of an interferometer is depicted in Figure 2. One requirement is that structures ranging from 10 to 50 meters in dimension must maintain their dimensions to submicron levels during its operational life of up to 30 years. Passive systems can not meet the requirements because they can not be assembled and validated to those accuracies on the ground, grow due to temperature changes, dimensions change when exposed to the space environment, and other factors. The requirement to actively adjust structures in space (Adaptive Structures) resulted in the development of in-line small stroke actuators. Figure 3 is a Control Structures Interaction (CSI) type active member design (Anderson et al., 1990) with a hole in the actuator for a quartz rod to measure the displacement change between the two ends of the member. The active member must support the structural loads through the actuator. Tensile strains in the actuator is avoided by mechanically pre-stressing the actuator 'in compression. Newer designs currently exists.

"The initial designs used high voltage actuators with thick PZT wafers to allow machining of a hole through the center of the PZT without it cracking. This required special amplifiers exceeding 1000 volts that are not compatible with the standard spacecraft 28 volt power supply. Both ceramic PZT and electrostrictive (PMN) actuators were used in the active member design. The mechanical design of the active member was changed from the actuator developed by Kaman (1988) to eliminate mechanical non-linearities. Flexures replaced the mechanical connections in the active member. The dimensions of the PZT wafer are 15mm OD, 7.1mm ID and is 66mm long. The dimensions of the PMN are 7.5mm OD, 4.9mm ID and is 66mm long. The PZT actuator is preloaded to 140# to allow for ± motion without applying a negative voltage and the PMN actuator is preloaded to 60# to operate at a biased voltage. For PZT the upper operating voltage is 1000v or (1000v/mm) and the PMN upper operating voltage is 30"OV or (1700v/mm). The specific details of the actuator material or its "as built" geometry are not available from the manufacturers. Some of the other characteristics of the two actuators are in Figure 4. Larger static load capacity of the active member is desired for launch or ground test conditions. However with larger loads, the diameter must be increased to keep the stress below the depoling stress which increases the capacitance and thus the power requirements.

Umland and Chen (1992) presents a low voltage active member (Figure 5) without a hole. The deflection measurement system is added to the end of the actuator. The dimensions are similar to the CSI actuator and active member. In addition, a portion of the PZT stack is used to directly measure the force in the PZT stack. All active members incorporates a load cell is series with the active member. The actuator design without the hole allowed the use of thinner wafers (problems were anticipated with drilling holes in thin wafers) and thus lower voltages. The thickness of the wafers is estimated to be 0.1mm and the maximum operational voltage is limited to 100v. This actuator was integrated into a truss structure for damping and static displacement tests. Several interesting characteristics of the actuator were noticed. Figure 6 is the variation in gain versus displacement and frequency and Figure 7 is the variation in gain versus time (cyclic loading) or aging. Recently, several low voltage actuators were fabricated with a hole in the center for incorporation into a CSI type active member with performance comparable to the PSR active member.

In-line actuators provide the capability to electronically change the stiffness of the actuator. In many of the active damping applications, the active member was electronically soften to reduce its stiffness by a factor of 1000. Active members have been stiffen by a factor of about 2.

The majority of the experiments using the active members in a variety of truss type structures ranging from 6 foot to 36 feet in dimension for active damping were very successful. These experiments require a small percentage of the 0.1% stroke available from the above actuators. The statically adjusted position of the structure was maintained by continually applying power to the actuators.

Several organizations incorporated magnetostrictive actuators into the PSR type active member because a hole through the actuator is not required. A magnetostrictive material referred to as Terfenol D (Butler, 1988) was used. The advantages of magnetostrictive materials appear to be (1) higher stiffness, (2) larger strains, (3) higher load capacity, (4) increased performance at cryogenic temperatures and (5) lower amplifier volt-amp requirement. The disadvantages appear to be higher mass and the generation of a magnetic field. JPL has not characterized the active members nor used them in a testbed to establish their performance. The (1) dependence on load, (2) hysteresis, (3) linearity, (4) repeatability, (5) return to zero position, (6) temperature dependence, and (7) other factors must be carefully evaluated. A table comparing magnetostrictive actuators to the PZT and electrostrictive materials are in Figure 8.

Future space application will require actuators operating over a wide range of temperatures from cryogenic to 700C and a larger load carrying capacity (1000# or larger). For static adjustments, a non-linear material is desirable to provide for predictable permanent static deformation without the continual application of power. Repeatability and reliability of the material is essential and linearity over the operational range of interest is highly desirable. Good design data or recommended design margins for various material properties for the design of the materials in spacecraft systems is required. Also specifications by which reliable actuators can be obtained is required.

Imbedded Actuators, Small Stroke

Imbedded actuators are primarily used to develop active members for use in truss type structures as discussed in the paragraph for in-line actuators. They have functioned well in ground experiments and have been incorporated into flight experiments by TRW. This type of actuator can be readily integrated into two-dimensional flat structures to provide damping.

Bronowicki et al. (1992) has embedded both Navy Type I and II PZT into thermoset and low temperature (550°F) thermoplastic composites for both actuation and sensing. The parameter El (the lateral modulus of elasticity) times D31(coefficient) is the best measure of the actuator's capability to transmit strain into the structure. To establish the strain limits of embedded actuators, a 7.5 mil thick PZT encapsulated in an insulating medium was embedded into a graphite composite with a modulus of elasticity comparable to PZT. Tests after straining the PZT to 4000 micro-strain indicated a loss in strain from ± 50 micro-strain to -50 to O micro-strain when voltage between ± 150v was applied. With further static tests, the ultimate design ultimate strain for embedded actuators for Type I and II was established at 600 and 1500 micro-strain. The reduction of E1xD31 decreases when stressed beyond 2500 micro--strain as shown in Figure 9. Navy type II PZT embedded into thermoplastic composite resulted in a reduction of E1xD31 at about 500 micro-strain.

The performance of embedded actuators during dynamic and thermal cyclic testing were determined by embedding 10 mil Type I and 7.5 mil Type II PZT actuators into graphite epoxy composite cantilever beams. The fatigue loads spectrum are shown in Figure 10 was followed by 12 temperature cycles from ±100°C. The fatigue loads reduced the 1st and 2nd resonant frequencies by 1.2% and the thermal cycles reduced the frequencies by an additional 0.5%. The capacitance of the actuators and sensors degraded by an average of 1% due to fatigue cycles and additional 1% due to thermal cycles. After the 1,500 "micro-strain fatigue test, the actuator's ability to transfer load into the composite structure deteriorated by at least -12% and an additional 10-30% due to thermal cycles. The ultimate design requirement was to keep the PZT strain below 1,500 micro-strain. The variation of the dielectric constant over the temperature range ± 100°C correlated well with available vendor data.

For most space damping applications, the strain required is small. The large strain capability is required to survive the high dynamic strains imposed during the ground vibration qualification tests and the launch of the structure into space.

Surface Actuators, Small Strain

Kuo (1992) used surface mounted PZT-5H material to correct for long wave length quasi-static deformation errors on composite hexagonal mirrors (a one meter and a one-half meter) panels that are 1.0" thick. The mirror face sheet is graphite epoxy and the core is aluminum. The goal was to correct the mirror to a surface accuracy of 3 microns rms. Changes in the shape of the mirror surface are expected from creep of the material during its 30 year life or response to thermal changes and gradients, or other unanticipated effects. The panel cured at above room temperature may be required to operate down at 100° K. The panel is expected to response in its lowest energy mode, namely those similar to the lower vibration normal modes. Another desire is to change the focal length of the mirror. As shown in Figure 11, 6 strips of 0.5"x3.0"x.039" were bonded using 3-5 roils ECOBOND 45. Five hundred (500) volts applied to the PZT 5H resulted in a displacement of about 9 micron for each strip or 27 micron along a radius. For the one-half meter panel, the change in third order zernike coefficient was relatively linear from -500v to 400V as shown in Figure 12. The deformation from the center to the edge at -500v corresponded to about 8.5 microns. The efficiency of the PZT/bond was about 30% when compared to the theoretical predictions.

Surface actuators or embedded actuators can be used to quasi-statically deform two-dimensional surfaces. For the experiment, continual voltage was applied to maintain the deformation correction. A desire exists for non-linear materials with the capability to permanently change their length without the application of power. Temperature range of operation may range from 100”K to greater than room temperature. A good material has high E1xD31 value at low voltages in the temperature range of interest. Repeatable material characteristics in its operational environment is required to accurately adjust the panel.

Large Displacement Actuators

Several mechanical leverage systems have been added in series with the in-line actuators to amplify its total stroke. The stiffness and the load capacity decreases proportionally with the mechanical amplification factor. Motion amplifications of up to 100 appear to be feasible.

Another requirement is for long quasi-static stroke (±0.25") actuator with a submicron displacement resolution. Bamford et al. (1993) used the inchworm concept to develop the actuator in Figure 13. The objective of the actuator is to provide the option of unloading the PZT when the active member is subjected to large loads during ground tests and launch. Voltage levels up to 1000v were used to drive the PZT actuator. The dimensions of the actuator are identical to the actuators described in the section on in-line actuator, small displacement. A typical curve of the actuator motion rate as a function of voltage is shown in Figure 14. The final fine resolution adjustment is by clamping one end and adjusting the voltage on the actuator to the desired displacement. The fine resolution capability subjected to various loads is shown in Figure 15 and corresponds to about 0.625 micron or 16v. In the configuration with one clamp open, the actuator can be used as a small stroke dynamic active member.

Other combinations of long stroke and high resolution actuators exists. One actuator consists of a long stroke (±.25") actuator is a ‘mechanical screw type actuator and a PZT actuator with a total stroke range that overlaps the resolution of the mechanical actuator.

The quasi-static long stroke actuators are valuable to control the internal loads within the structure during deployment as described by Wada and Utku (1992) , to statically adjust the shape of structures, to preload the joints or to slowly adjust the shape of the structure when subjected to slowly varying therma 1 deformations.

Deformable Mirrors, Short Wave Length Correction

The developments to place a large number of small piezoelectric or electrostrictive actuators behind a flexible mirror to correct for small wave length errors are not covered in this paper but Ealey (1991) presents an overview. The electrostrictive actuator used for some of the applications is described in the section on Articulating Fold Mirror for the Wide Field Planetary Camera II.

Composite Actuators, Small Stroke

The potential use of PZT actuators directly in the load path for small motion control, stiffness adjustment or active damping initiated a program to evaluate the use of PZT rods in a matrix material described by Darrah et al. (1991) . Small washer type actuators were fabricated with the *cross* section dimensions identical to the small displacement in-line actuators. A large number of stacks can be used to replace the actuator in the in-line actuator. Three different matrices with the PZT rods were investigated. The objective is to develop an actuator with high fracture toughness to avoid brittle cracking at low stress levels. Tests on these actuators are in progress at JPL.

Ceramic Applique, Cold Finger

As part of a space flight experiment (Glaser et al. (1993), Kuo et al. (1993) used a PZT ceramic applique to control the motion at the tip of a cold finger of a cryocooler. Figure 16 illustrates the applique PZT and Figure 17 illustrates the uncut PZT configuration and the use of a stacked PZT 5H material using the D33 actuation mode. The objective of the cryocooler is to cool an Infrared Detector. attached to the tip of the cold finger to 90°K while attenuating its motion as the cooler is vibrating and the cold finger structure is distorting due to 60 psi internal pressure oscillation at 60 Hz. The task was to develop an applique actuator on the cold finger that can counteract the 2-3 micron peak-to-peak motion anticipated at the cold finger tip.

The design was to place the shortest possible PZT near the base of the cold finger that is near room temperature (higher PZT performance and PZT thermal load of 0.1 watt less significant), reduce the thickness of the PZT for performance, and to reduce the voltage. The goal was to limit the voltage to one-half the poling voltage. The PZT-5H material was selected (0.6" high and 0.032" thick) with the slit configuration shown in Figure 16 to control both the axial and lateral motions. The required voltage level is estimated to be 640 volts.

The selection of the adhesive material and its control was critical to transfer the PZT strain into the coldfinger, to provide controlled actuation and to avoid electrical shorting. If each of the three actuator elements strain transfer efficiency differs, then the coldfinger will displace laterally when identical voltage is supplied to all three actuators. Trapped bubbles decreases the electrical isolation. The adhesive thickness was controlled to .001" using .001" diameter thread. Independent adhesive tests were performed using PZT bonded to an aluminum strip. The displacement transferred into the aluminum by the PZT is shown in Figure 18. No degradation of displacement was noted when cycled 10,000 times from ± 400 volts. Adhesive HY-SOL 9396 was selected because of its performance and is space qualified. The adhesive was 80% efficiency in transferring strain.

"The coldfinger was pressurized to 1000 psi before the applique was applied to pre-compress the PZT to avoid tensile *stresses* during . its operation of ± 60 psi around a mean pressure of 500 psi. Since the adhesive may creep and relieve the compression in the PZT, cyclic tests without compression were performed. The system was cycled to 500 million cycles using 600v at 200 Hz without degradation. The system was tested in a vacuum chamber down to 190°K and the performance degradation was comparable to the published curves.

The PZT stack design with actuators in the D33 direction to obtain larger motion with lower voltages were not considered when the first set of actuators cracked during shipping or subsequent handling.

For t"his class of application, the desire is for higher displacement/voltage actuators, long fatigue life, lower voltage systems, capability to withstand tensile stresses, tensi'le stress allowable and reliability. Information on the adhesives and their reliable strain transfer efficiency for the anticipated environmental and service conditions is required.

Articulating Fold Mirror (AFM), Wide Field Planetary Camera II (WFPC-II)

Fanson and Ealey (1993) developed an articulating fold mirror (AFM) for the WFPC-II to remain in its ground aligned "home" position within ± 10 arc sec through launch and transition to on-orbit environmental conditions, and to return to the "home" position automatically should there be a failure in the actuation electronics of the AFM subsystem. Figure 19 shows the AFM. The alignment precision required for the WFPC-II to correct for the

Hubble Telescope wavefront error was an order of magnitude more stringent than the original tolerances for the WFPC. In additional circumstantial evidence suggested that the on-orbit alignment of WFPC was drifting over time. The functional requirements were:

Table 1 Functional Requirements

Tip/Tilt Range	≥ ±206 arc sec (±1 mrad)
Short Term (2000 second) Stability	≤ ±1.8 arc sec
Long Term Stability	≤ ±13.6 arc sec
Ground-to-Orbit Stability	≤ ±10 arc sec
Repeatability	≈ ± 1% (±2 arc sec)
Tilt Step Size	≈ arc sec

The packaging constraints to place the actuation device within the existing space eliminated a conventional motor and gear-train approach. Three alternative solid state prime movers were evaluated. Magnetostrictors and piezoelectrics would have required the addition of feedback sensors in the AFM to meet the -repeatability and stability requirements due to their hysteresis and tendency to drift. Electrostrictive ceramic composed of lead magnesium niobate (PMN) offered the required precision.

The key requirements on the actuators were (1) the material returned to its zero position at zero voltage, and (2) the voltage-micro strain characteristics are repeatable over the temperature range of interest. During the 2000 sec observation, the temperature of the actuator was maintained within .07° C. Using a thermocouple on the system to establish temperature, the voltage required to rotate the mirror to a specified level is established.

The characteristics of the electrostrictive materials are shown in Figures 20 and 21. Figure 20 represents three complete cycles at 1 Hz. The response of the actuator is a function of time as noted in Figure 21. The dependency on time is evident in Figure 20, the curve -for -6°C that was generated at 1 Hz. The material didn't return to its original point and the second and third cycle differs from the first cycle. The actuator segments are approximately 0.340 inches in length and consist of approximately 39 active layers, each .007 inches thick. Itek suggested a safe limit for strain of about 450 microstrain. Three hundred (300) microstrain was used for the AFM that corresponds to an applied voltage of about 90 volts at room temperature with a linear stroke of 2 microns. The actuator was subjected to tensile stresses. The tensile allowable for design was 500 psi. From the test results shown in Figure 22, the 3 sigma value allowable is 1188 psi compared to the Itek design allowable of 1000psi.

Other requirements and data of the AFM program are (1) the bakeout temperature is 125°C, (2) the desired operational temperature is about 0°C, (3) actuator cycled 4 times between -15°C and +40°C with one hour soak at +40°C and one-half hour at -15°C, (4) at 10″C the AFM is repeatable within ±1%, (5) the AFM zero strain state was stable within 2 arc see, (6) AFM reached stable tilt within 10 seconds, (7) 1000 cycles at 10° C from O to 90 volts, (8) passed the vibration tests, and (9) no observable drift of the mirror position after 100 krad proton radiation test. The adhesive material selected for the actuator bonds is EpoTek 353ND epoxy.

SUMMARY

The paper lists different types of precision space actuators for various ground and, flight applications. Actuators are being integrated into flight systems without reliable material design data base. Where possible, conservative design margins on the material properties are used. The users and developers of actuators must develop a mutually acceptable specification that help produces reliable actuators that meets the performance requirements.

The requirements for each space application differ. Requirements on the actuator material may include: (1) temperature of operation in the range from 1°K to 31O"K, (2) capability to carry tensile stresses, (3) capability to carry high compressive stresses, (4) ability to transfer strains to structural materials, (5) low voltage and power, (6) high strain, (7) high fatigue life, (8) linearity, (9) repeatability, (10) low outgassing system, (11) impervious to high space radiation environment, (12) shock resistant, (13) high bandwidth, (14) stable, (15) reliable, and (16) others.

ACKNOWLEDGEMENTS

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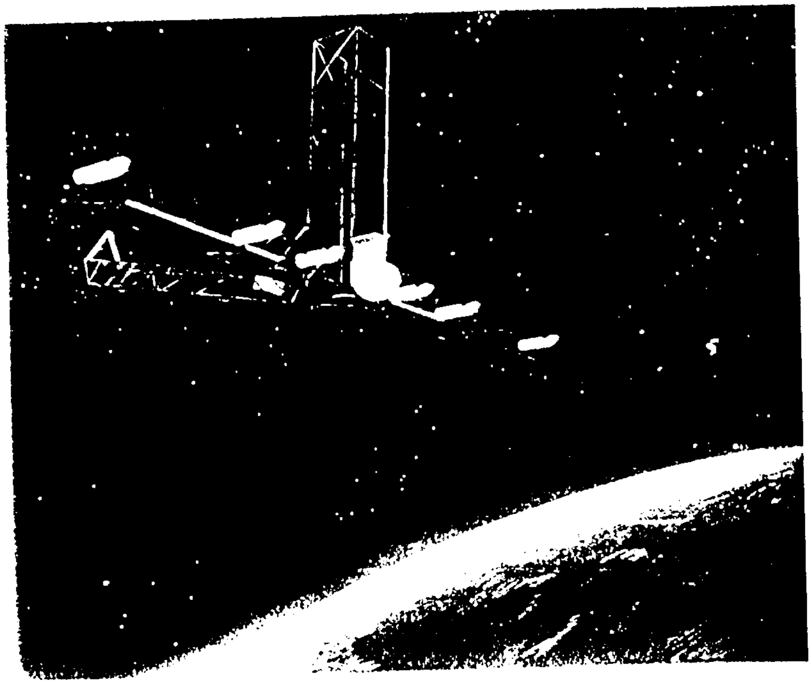
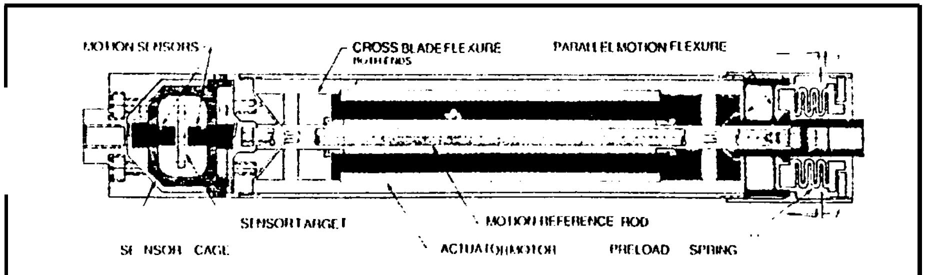
A ... Adaptive Structures
B ... Sensory Structures
C ... Controlled Structures
D ... Active Structures
E ... Intelligent Structures

Figure 1 [illegible]

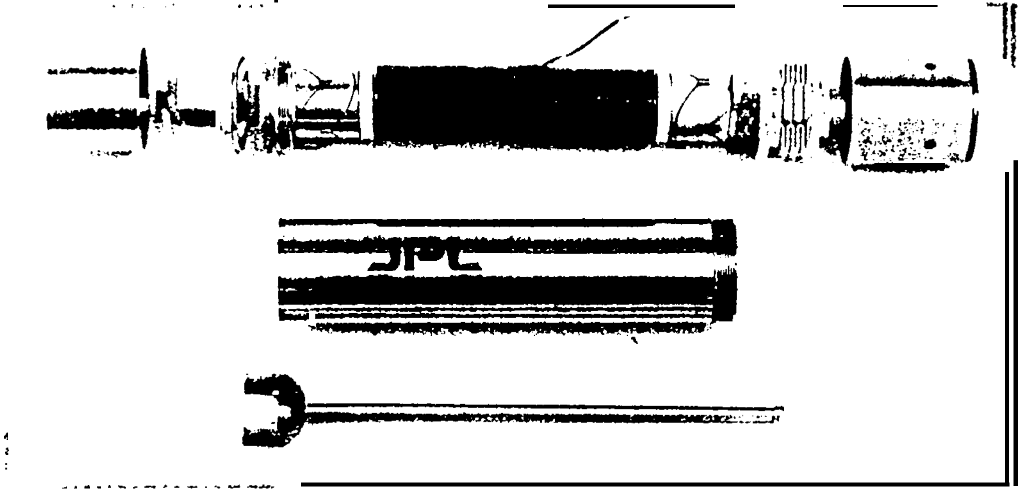


JPL

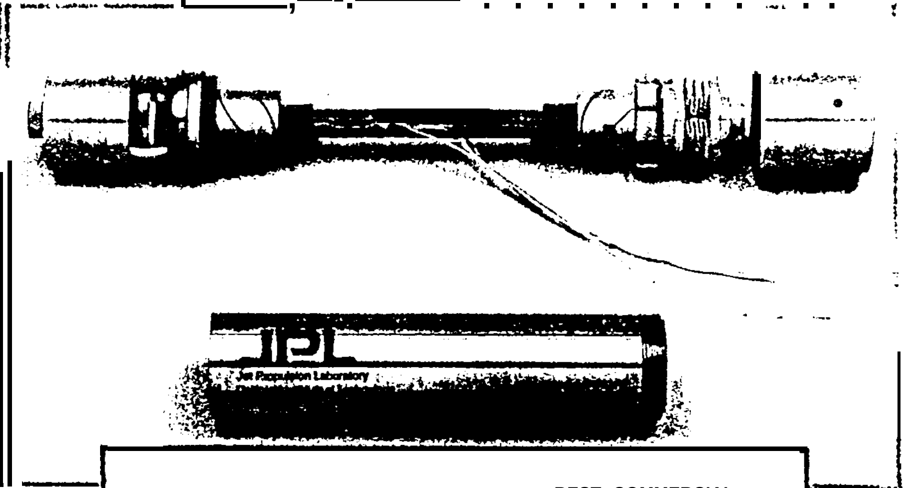
2ND GENERATION ACTIVE MEMBER

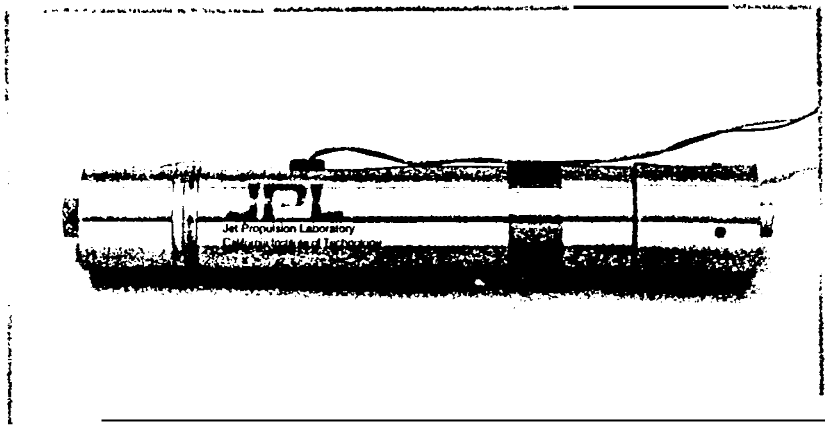


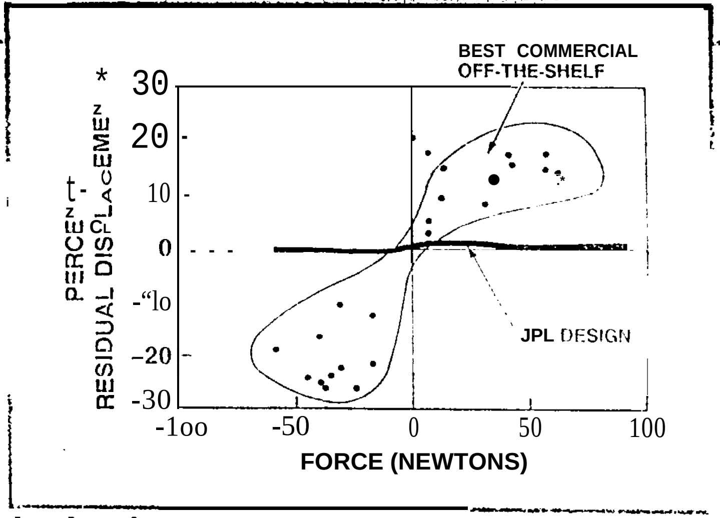
PZT Member



PMN Member







Inelastic Behavior

Figure 3 2nd Generation Active Member

Property	PZT[1]	PMN
Stiffness (short circuit)	14.6 N/pm (83.6 lb/mil)	9.75 N/μm (55.7 lb/mil)
Mass	240 g (0.53 lb)	190 g (0.42 lb)
Maximum Operating Voltage	1000 V	300 V
Normal Bias Voltage	500V	150 v
Single Wafer Thickness	1.0 mm (39.4 mils)	0.18 mm (7.0 mils)
Displacement (1 Hz)	63.4 μm (2.50 mils)	39.S μm (1.56 roils)
Force (1 Hz)	505 N (114 lb)	455 N (102 lb)
Hysteresis (1 Hz)[2]	16.0 %	1.2 %
Capacitance (25 Hz)[2]	0.6 μF	7.6 μF
Current, rms (25 Hz)[2]	33 mA	127 mA
Temperature Sensitivity	n. a.	1.2% /°C

[1] Average of 2 members
[2] For maximum displacement

Figure 4: Active Member Specifications

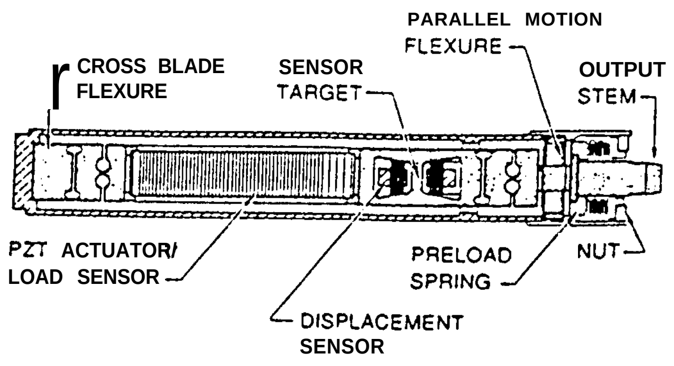


Figure 5 PSR Active Member

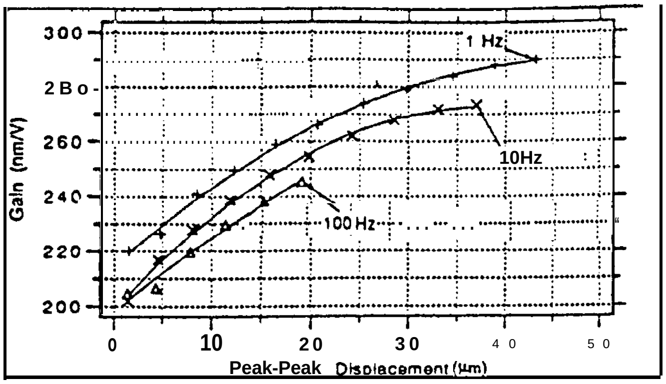


Figure 6 Gain vs Frequency

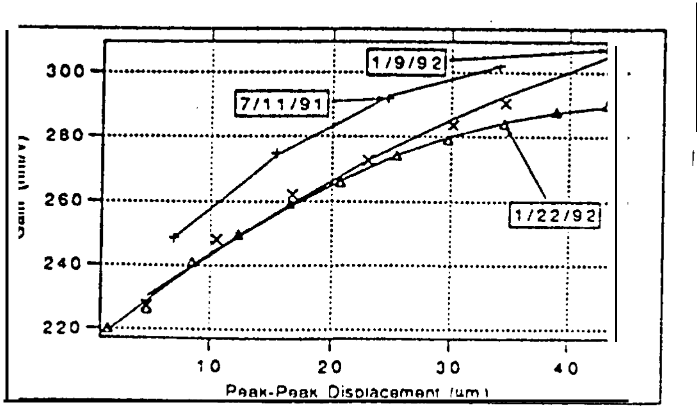


Figure 7 Gain vs Number of Cyclic Loads (Aging)

Property	PZT RT	PMN RT	TERF-D RT	TERF-D Cryo	MAG. X Cryo
Displacement (micron)	64"	40	50	42	205
Force (Newtons,N)	505	455	1000	540	750
Hysteresis (percent)	16	1.2	16	31	5.3
Stiffness (N/micron)	14.6	9.8	28	18	14
Mass (grams)	240	190	.457	500	495
Max. Oper. Volts	1000	300	5.5	2.1	1.6
Normal Bias Volts	500	150	0	0	0
-Current (amps peak)	.046	.180	2	2	1.5
Peak V-A (volt-amp)	46	54	11	4.2	2.4

Figure 8. Comparison of In-Line Actuators

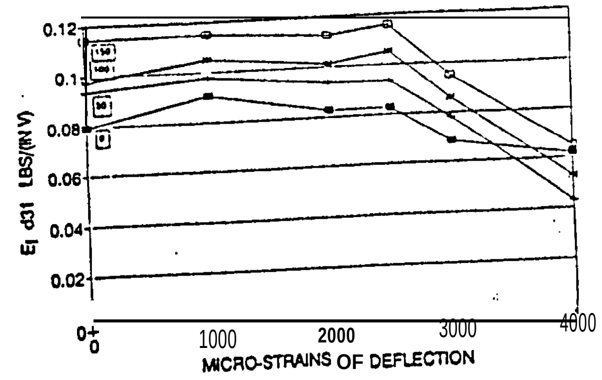


Figure 9 Computed E_1d_{31} as a Function of Applied Strain At Various Peak Voltage Levels for Navy Type II in Thermoset.

9

Type - Schedule	Load lb	Strain μ-ε	% of limit	# of cycles
I-a	1,500	360	60%	100
1-b	2,500	600	100%	10
	2,000	480	80%	50
	1,500	360	60%	800
11-a	4,200	90()	60%	100
H-b	7,000	1,500	100%	10
	5,600	1,200	80%	50
	4,200	900	60%	800

10

Figure 10 Cyclic Loads

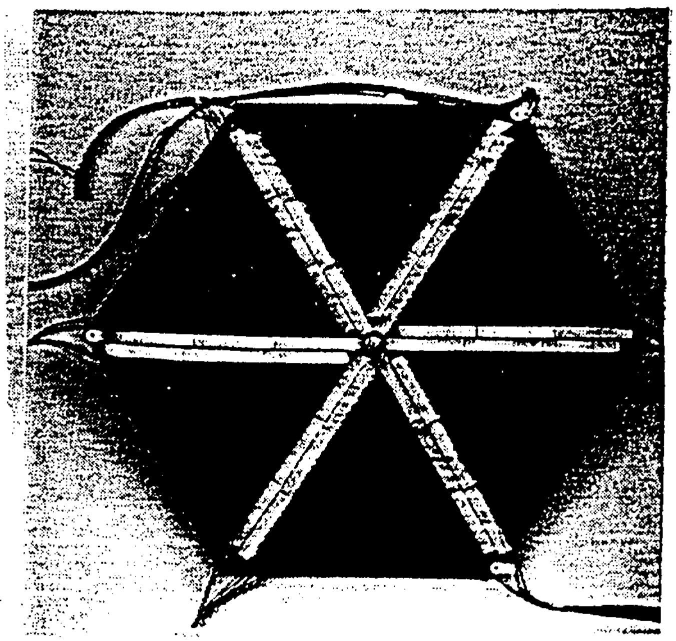


Figure 11 One-half Meter Composite Panel with PZT

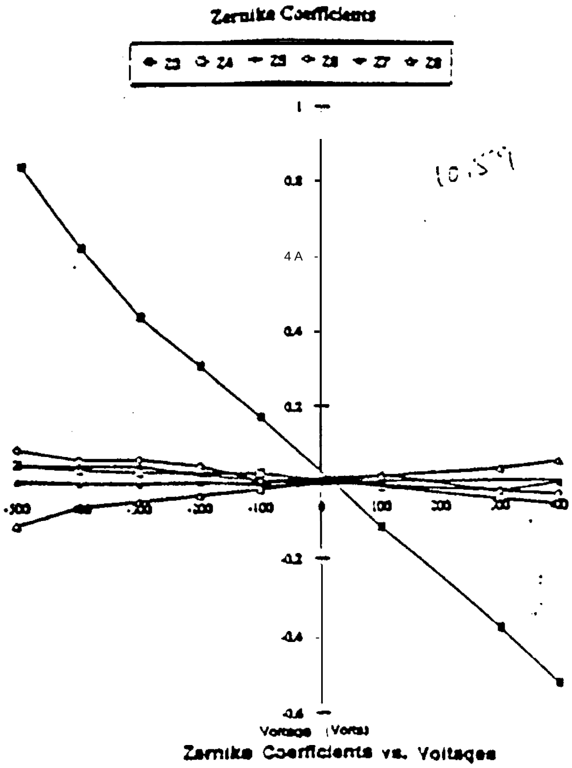


Figure 12 Zernike Coefficients VS Voltages

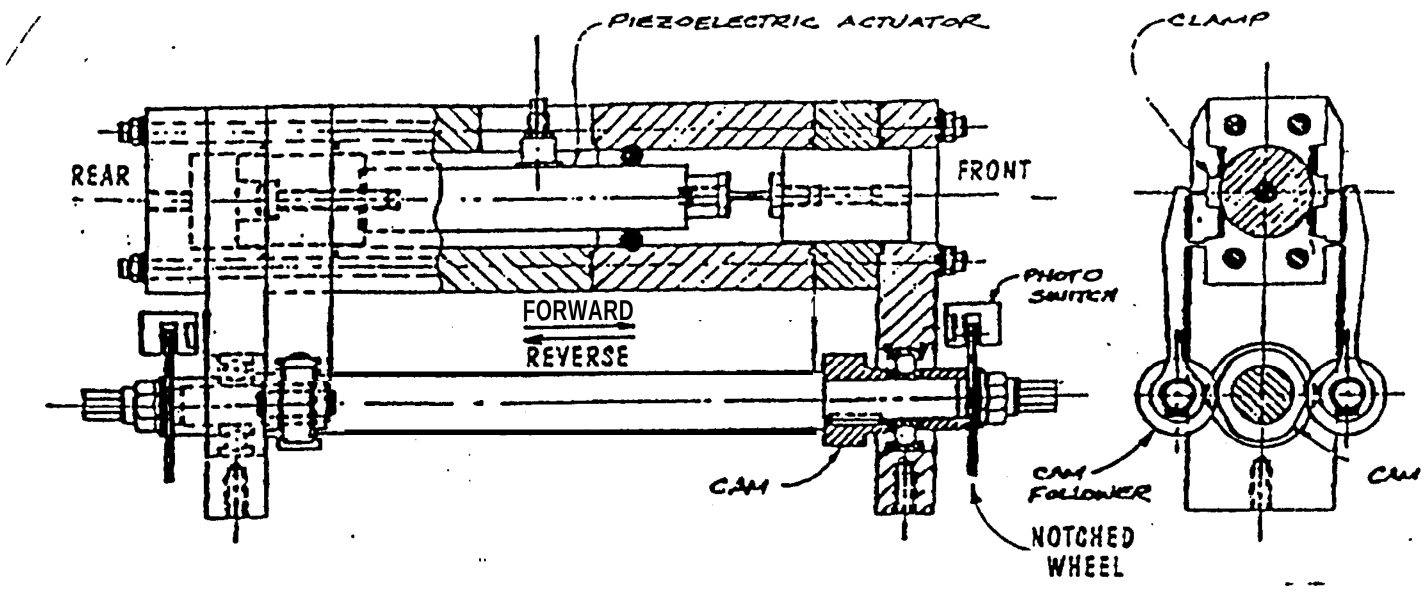


Fig. 13 Mighty Worm Actuator

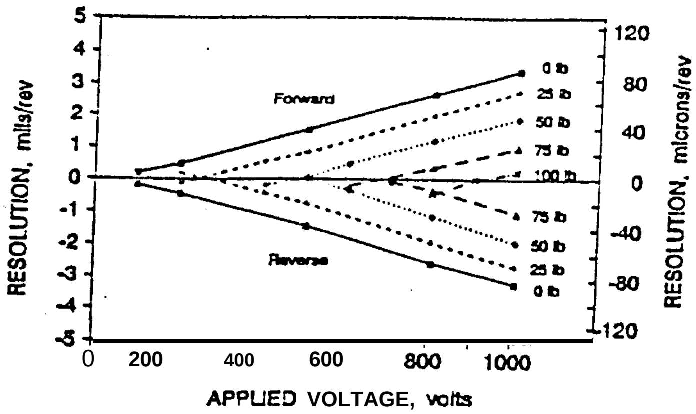


Fig. 14. Mighty Worm Long-Stroke Load Resolution.
" Forward and Reverse Travel, 60 rpm

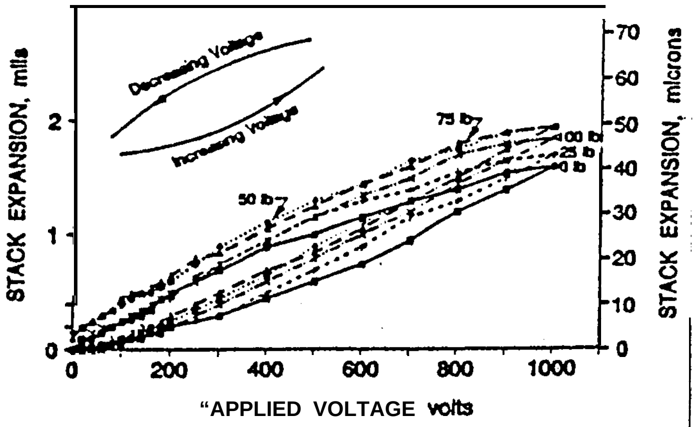


Fig.15. Mighty Worm Incremental Positioning. Increasing and Decreasing Volts, [illegible]

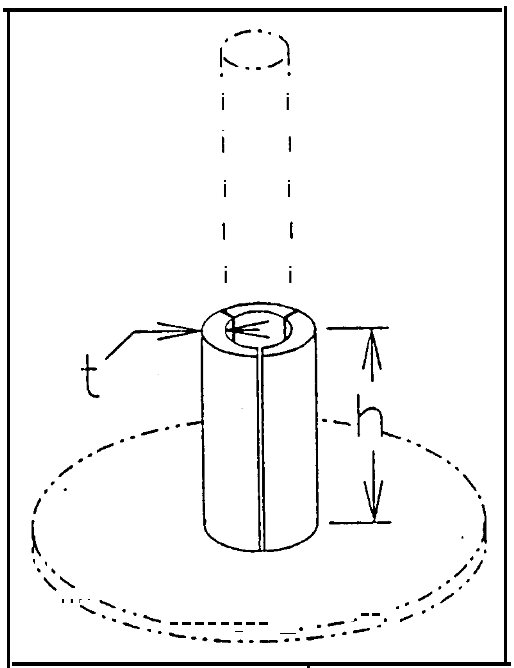


Figure 16 Ceramic Geometry

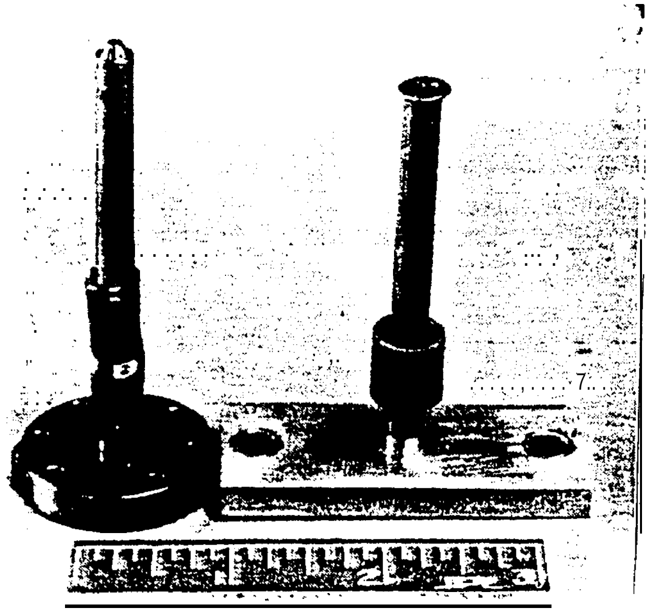


Figure 17 Coldfingers

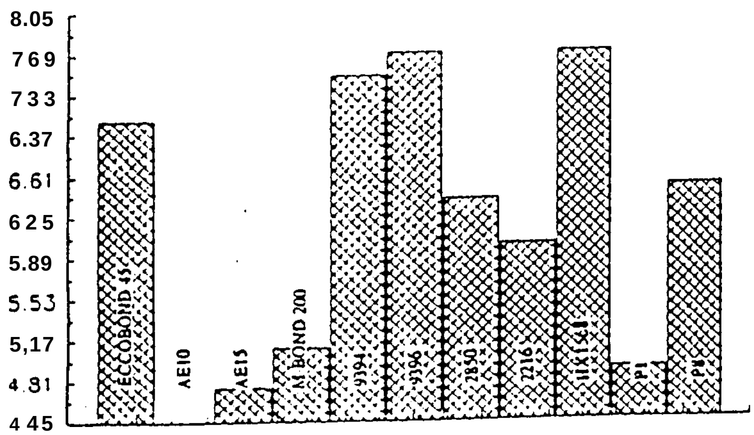


Figure18 Adhesive Test Results

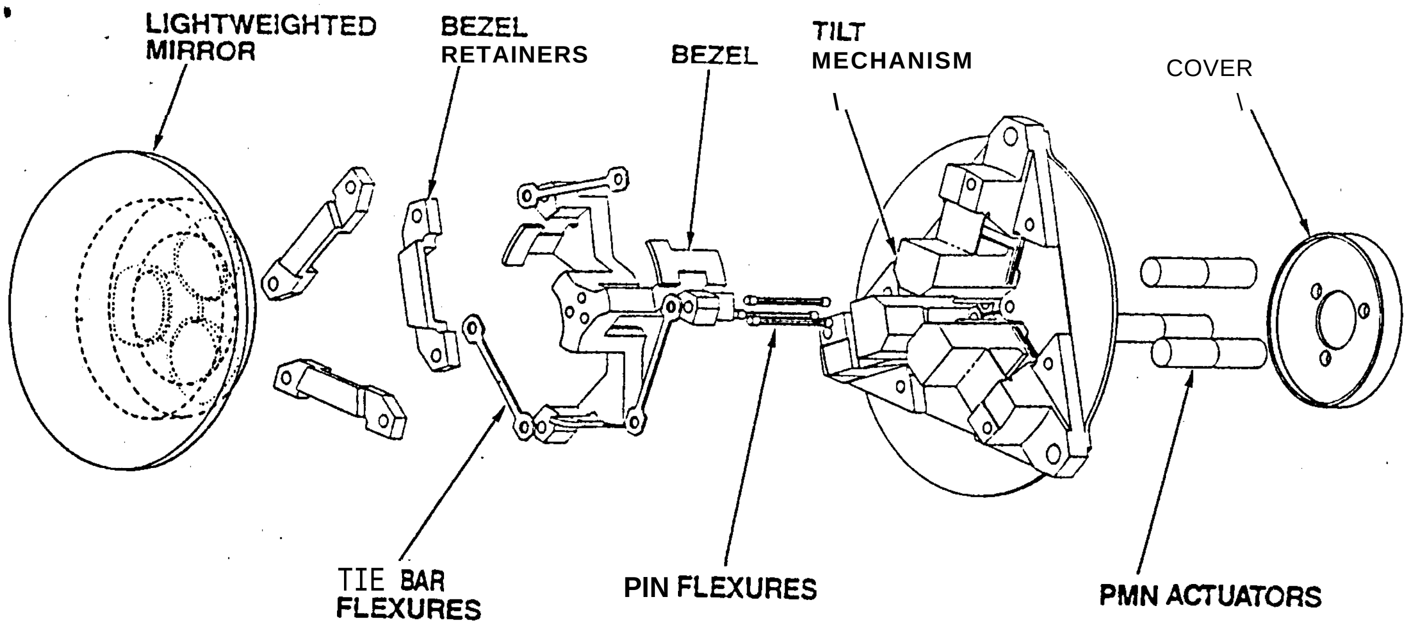


Fig.19. Exploded view of Articulating Fold Mirror.

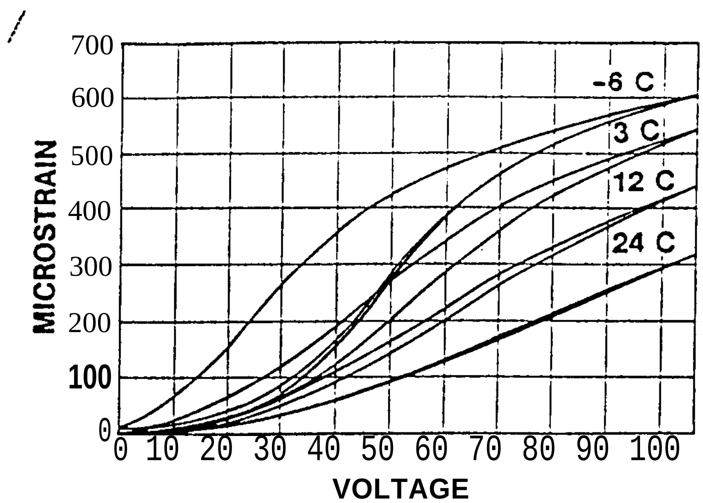


Fig.20 Electrostrictive actuator strain vs. voltage at various temperatures.

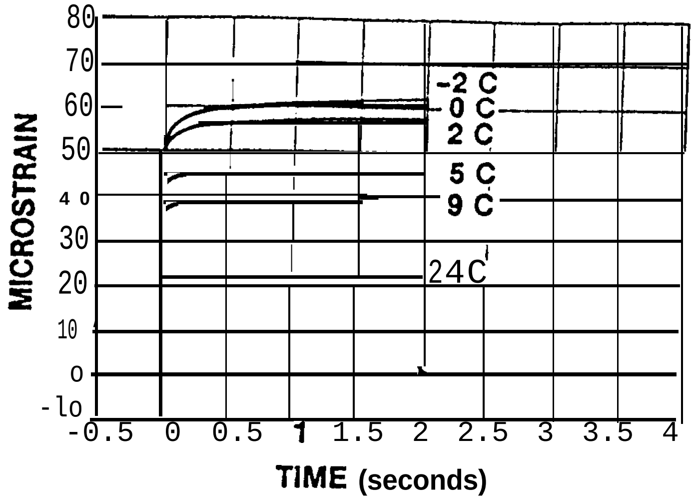


Fig. 21 Actuator response to step voltage change showing stable zero strain state.

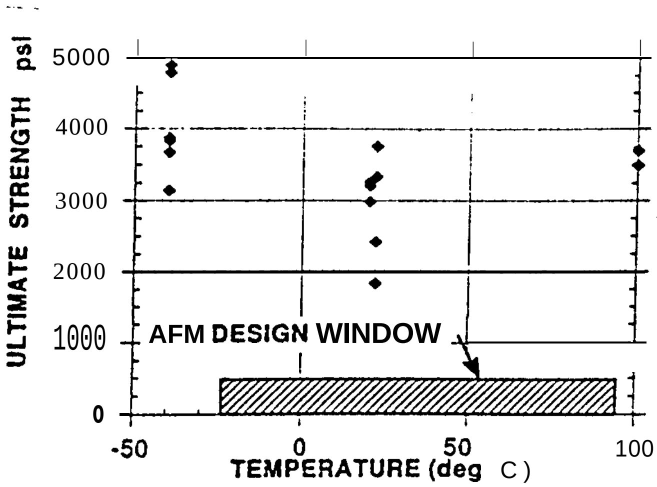


Fig. 22 Electrostrictive actuator pull test results.